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INVESTIGATION OF PLASMA DRIFT AND EQUILIBRIUM IN TOROIDAL MAGNETIC FIELD WITH DIVERTOR

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ABSTRACT. Experiments conducted with "Sirius" stellarator divertor showed that the divertor magnetic field ensures stability of the plasma inside this surface and equilibrium of the plasma in the toroidal magnetic field.

INTRODUCTION /303*

It is well known that toroidal magnetic fields cannot ensure plasma equilibrium because of the presence of centrifugal and gradient charged particle drifts, as a result of which an electric polarization field arises perpendicular to the magnetic field, causing drift of the plasma as a whole in the direction of the large radius of the torus. Equilibrium of a plasma column in closed magnetic traps can be achieved in several ways. For example, rotational transform of the lines of force removes the electric polarization field if the entire trap perimeter is filled by the plasma [1]; in toroidal systems with current flowing through the plasma along the lines of force of the restraining magnetic field, achievement of equilibrium is possible with application of small magnetic fields perpendicular to the basic magnetic field [2]. A plasma column may be in equilibrium if it is bounded by a metallic diaphragm. In this case the depolarization currents, flowing along the magnetic lines of force and reducing markedly the electric polarization fields, close through the diaphragm [3].

However, it was shown in [3] that the equilibrium provided by metallic diaphragms is disturbed as soon as the charge separation current begins to exceed the ion saturation current to the diaphragms. Moreover, the presence

*Numbers in the margin indicate pagination in the original foreign text.

of metallic diaphragms inside the plasma volume is not desirable, since contact between the plasma and diaphragm leads to vaporization of the latter and influx of impurities.

Rotational transform of the magnetic field lines of force cannot remove the plasma polarization if conductivity is not provided along the entire length of the line of force. This is a serious drawback when filling the closed plasma trap by means of external injection.

In experiments on plasma injection through the magnetic slots of a divertor [4, 5], it was shown that — as a result of the plasma filling the annular region, where the magnetic field equals zero (Figure 1), and propagation of the plasma from this region along the magnetic lines of force — a stable cylindrical plasma formation is created whose diameter is equal to the diameter of the divertor surface (the divertor surface is the surface formed by the lines of force separating the magnetic flux diverted into the divertor chamber from the magnetic flux traveling along the divertor). It was found that the "walls" of the plasma cylinder prevent both drift of the plasma across the magnetic field from its interior region and penetration of the plasma into it. The cylindrical plasma formation on the divertor surface /304 is stable, since there the quantity $U = -\int \frac{dl}{B}$ is minimal [6]. It appears to us that the micropicture of the deceleration and stopping on the plasma cylinder of the plasma streams drifting across the magnetic field amounts to closure of the transverse electric fields through the divertor annular null magnetic field line. The presence of the divertor annular min-B region also leads to stabilization of the plasma relative to macroscopic disturbances [7]. The stability of such a configuration is also shown in [8].

On the basis of this analysis we can assume that when the divertor magnetic field is combined with the toroidal magnetic field the stabilizing

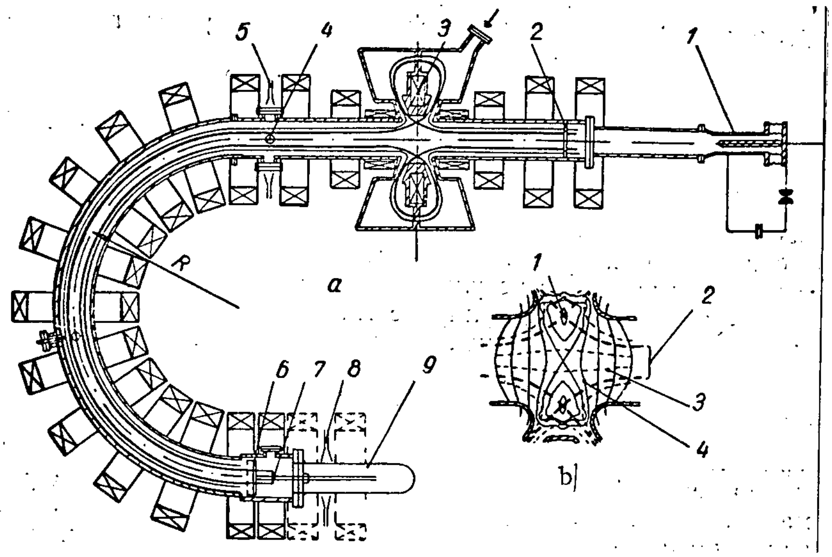

Figure 1. a - schematic of setup: 1 - plasma injector; 2 - diaphragm; 3 - divertor central coil; 4 - electrostatic probe; 5,8 - microwave interferometer horns; 6 - collector probe, plasmascope; 7 - magnetic aperture; 9 - glass chamber; b - lines of force and H = const lines in longitudinal section of divertor: 1 - point H = 0; 2 - magnetic aperture; 3 - lines of force; 4 - H = const lines.

action of the divertor surface, filled with plasma, is retained because of good electrical conductivity of the plasma along the magnetic lines of force, i.e., by the good electrical coupling with the "plasma diaphragm" in the annular divertor region where the magnetic field equals zero. This should lead to reduction of the toroidal drift and equilibrium of the plasma cylinder.

The present experiments were devoted to verification of these assumptions.

EXPERIMENTAL SETUP

One end of the Sirius stellarator divertor [9] was connected with a semitorus whose large radius was 40 cm; the inside diameter of the tube was

7.0 cm (Figure 1,a). A coaxial plasma injector used to inject plasma along the system axis was installed at the other end of the divertor. The cross section of the plasma stream at the inlet to the divertor was bounded by a 3.5-cm-diameter diaphragm, exceeding somewhat at the given section the diameter of the magnetic aperture, so that the plasma filled the divertor surface. The coils creating the longitudinal magnetic field on the toroidal segment were connected in series with the divertor magnetic system and made it possible to obtain a magnetic field in the semitorus up to 10 KOe. By altering the current direction in the divertor central coil, it was possible to create either a divertor or solenoidal field configuration on the rectilinear segment of the system. /305

Observations of plasma passage along the system were made with the aid of a plasmascope and screened electrostatic probe, mounted at the free end of the semitorus. The duration of the voltage pulse on the plasmascope could be varied from 1 to 100 μsec, which made it possible to study the cross section form of both the entire slug as a whole and its individual parts.

MEASUREMENTS

Figure 2 shows plasmograms of the integral luminosity of plasma traveling along the semitorus for divertor (above) and solenoidal (below) magnetic field configurations as a function of the intensity of the toroidal magnetic field. We see from the figure that while in the conventional toroidal solenoid field we observe drift of the plasma as a whole toward the outer wall of the chamber, in the case of the divertor configuration the picture changes markedly. With a field of only 3 KOe (Figure 2) the plasma stream is localized in the region near the axis and its transverse dimensions coincide exactly with the dimensions of the divertor magnetic aperture (the magnetic aperture is the area surrounded by the divertor surface). However, the outer edge of the plasma stream, propagating exactly along the center of the chamber, is unstable. This shows up in the form of a narrow plasma spike

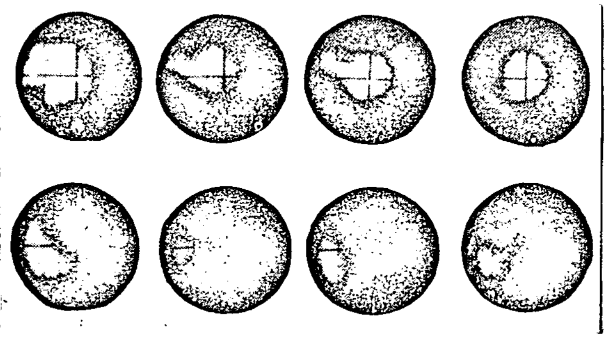

Figure 2. Integral plasmograms of plasma stream cross section. From left to right: H = 2, 4, 6, and 7 KOe.

to the outer wall of the chamber. The contribution to the integral plasma luminosity due to this spike decreases markedly with increase of the magnetic field intensity, and for an intensity of 7 KOe instability of the outer edge of the stream is practically absent. It appears that the plasma spike is due to toroidal drift of the peripheral layers of the stream, which are not directly coupled with the annular divertor null field line. Thus the plasmascope observations indicate the absence of toroidal plasma drift in the curvilinear field with divertor.

The plasma instability in the form of a spike from the surface of the equilibrium plasma stream in a toroidal field with divertor was studied in more detail with the aid of a plasmascope operating in the pulsed regime. We were interested in clarifying what part of the slug was most subject /306
to toroidal drift. Figure 3 shows photographs of the stream cross section at different times relative to injector triggering. The plasmascope pulse duration was 2 μsec and the intervals between frames were 2 μsec, so that the pictures shown characterize practically the entire slug along its length. Figures 3,a,b,c,d were obtained for the stream density front, with Figure 3,b corresponding to the density peak, while the remaining frames were taken in the process of stream density reduction and characterize the behavior of the slowest "tail" portion of the slug. We see from Figure 3,a that the most energetic part of the stream is unstable with respect to toroidal drift, as in the conventional solenoidal field. This may be explained by the fact that the fastest part of the slug can transit the semitorus prior to the moment of formation of the stable plasma ring in the divertor min-B region, which is confirmed by Figure 3,b, from which we see

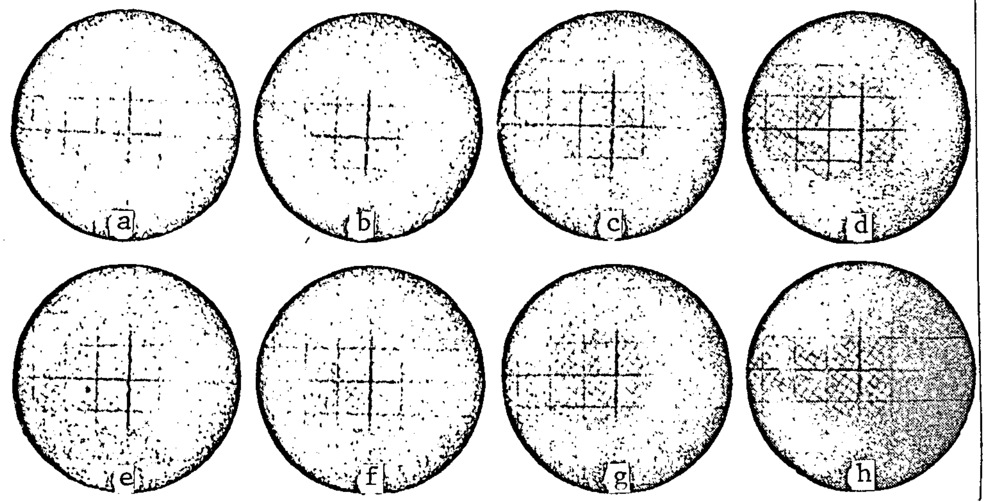

Figure 3. Form of plasma stream cross section at different times for divertor configuration of magnetic field. Time runs from left to right starting in the upper row of plasmograms.

that the subsequent portion of the stream forms a hollow cylinder and the part of the slug intermediate between the times corresponding to Figures 3,a and 3,b is no longer associated with the basic cylindrical stream (radial spike in Figure 3,b). However, a plasma spike in the direction of the large radius of the torus is also observed for subsequent moments of time, i.e., the outer edge of the slug as a whole is unstable owing to the toroidal configuration of the magnetic field. In this case the plasma inside the divertor surface is unstable with respect to toroidal drift.

A somewhat different picture is observed for the "tail" part of the slug. Development of plasma "tongues" is also observed in the favorable curvature direction, i.e., in the direction of magnetic field intensity increase, but their drift in all cases is directed toward the large radius of the torus. The macroscopic disturbances of the slug edge, which are quite marked for the "tail" part of the slug, were not studied in detail in the present experiment. However, we can hypothesize that the observed "spikes" arise as a result of the presence of a radial electric field in the plasma, which may be responsible for the appearance of the "centrifugal" type instability [10]. It was shown in [7] that the instability of this /307 type is apparently weakened markedly in magnetic fields of the divertor configuration, since the transverse electric fields which develop at the edge can short through the region in which the divertor field is zero. However, if the slug length is less than the length of the toroidal segment, separation of the "tail" part of the plasma from the annular zero magnetic field region is possible. In this case shorting of the electric fields through the "plasma diaphragm" terminates and the toroidal drift of the slug increases.

It follows from the observations presented that, although drift of the plasma as a whole in a curvilinear magnetic field with divertor is not present, plasma losses owing to toroidality are not completely eliminated because of instability of the peripheral layers of the stream, which do not have electric coupling with the annular region of divertor null magnetic field.

Charged particle losses to the chamber walls can be assessed by comparing the number of particles entering and leaving the toroidal field. Figure 4 shows the ratio of the plasma losses ΔN along the semitorus to the total number N of particles at the entrance to the toroidal segment as a function of magnetic field intensity. The ratio is compared for the divertor (curve I) and solenoidal (curve II) field configurations. In the toroidal field with divertor the ratio $\Delta N/N$ decreases with increase of the field as H^{-1}, while in the solenoidal field the decrease is linear. The curve for the divertor configuration approaches zero. In the solenoidal field with maximal field intensity 6 KOe the plasma particle losses to the walls are large, and amount to 60% of the total number of particles in the slug, which corresponds well to the

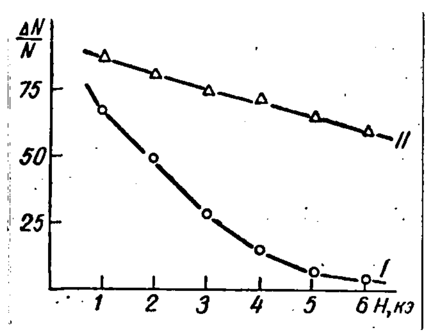

Figure 4. $\Delta N/N$ versus H: I - divertor configuration; II - solenoidal configuration.

analogous measurements described in [11]. The relative losses of particles leaving the region bounded by the divertor surface are somewhat greater. The number of particles inside the aperture at the entrance to and exit from the semitorus differs by a factor of 1.5, while the corresponding ratio of average density across the aperture section is $n_{ent}/n_{ex} = 3$ (in the solenoidal field the ratio is about 35-40). This situation may be associated with some redistribution of the stream density along the radius and also along the length of the slug. For example, it appears to us that local variations of the plasma density because of instability of the peripheral layers of the stream may lead to change of the density profile and therefore to decrease of the plasma average density across the section of the magnetic aperture during a time on the order of the time for the slug to transit the system.

CONCLUSIONS

As a result of the studies we can conclude that the divertor magnetic field, having a minimum potential $U = -\int \frac{dl}{B} \Big|$ surface, ensures stability of the plasma inside this surface and equilibrium of the plasma in the toroidal magnetic field. Beyond the limits of the magnetic aperture, the plasma is stable with respect to toroidal drift because of the absence of electric coupling with the annular plasma diaphragm formed in the divertor magnetic field null region. /308

This property of the divertor surface makes it possible to guide a plasma with low losses along the toroidal segments of closed magnetic traps with injection through the magnetic slots of the divertor. For retention and long-term confinement of the plasma inside the magnetic aperture, it is obviously necessary that the plasma be retained for a long time on the divertor surface. Because of the constructional characteristics of the "classical" divertor with continuous disk partition between the central coil and the chamber wall, there will be plasma losses from the divertor surface on this partition and plasma "leakage" through the magnetic slots into the divertor chamber, and its place will be occupied by the plasma located inside the aperture. However, the plasma losses on the divertor surface can be compensated by reinjection through the slots. Moreover, it appears that the plasma losses from the divertor surface can be reduced significantly by replacing the continuous disk partition by small-area local supports for the central coil.

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